Semileptonic D Results at CLEO-c

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Representing the CLEO Collaboration

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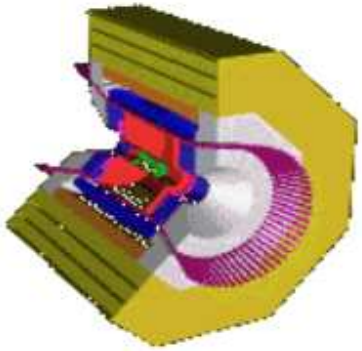


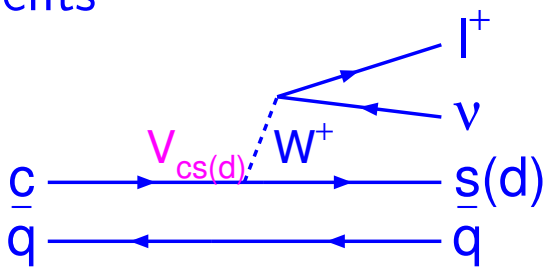
Topics

- Inclusive D semileptonic decays (hep-ex/0604044)
- Form factors, and V_{cs}, V_{cd} from $D \to K/\pi e^+\nu$
- First measurement of form factors in $D \to \rho e^+\nu$
- Form factors in $D^+ \to K^-\pi^+e^+\nu$ (PRD **74**, 052001 (2006))
- First observation of rare decays $D^+ \to \eta e^+\nu$, $D^0 \to K^-\pi^+\pi^-e^+\nu$
- Data Sample: 281 pb^{-1} at the $\psi(3770)$
- All results are preliminary except $D^+ \to K^-\pi^+e^+\nu$ published

Why D Semileptonic Decays

- D Semileptonic Decays and CKM matrix elements

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



- Inclusive semileptonic Decays $D \to X e^+ \nu$
  - Lepton spectra and BR's (theorectical predictions)
- Exclusive $D^0 \to K^- e^+ \nu$, $\pi^- e^+ \nu$, etc.:

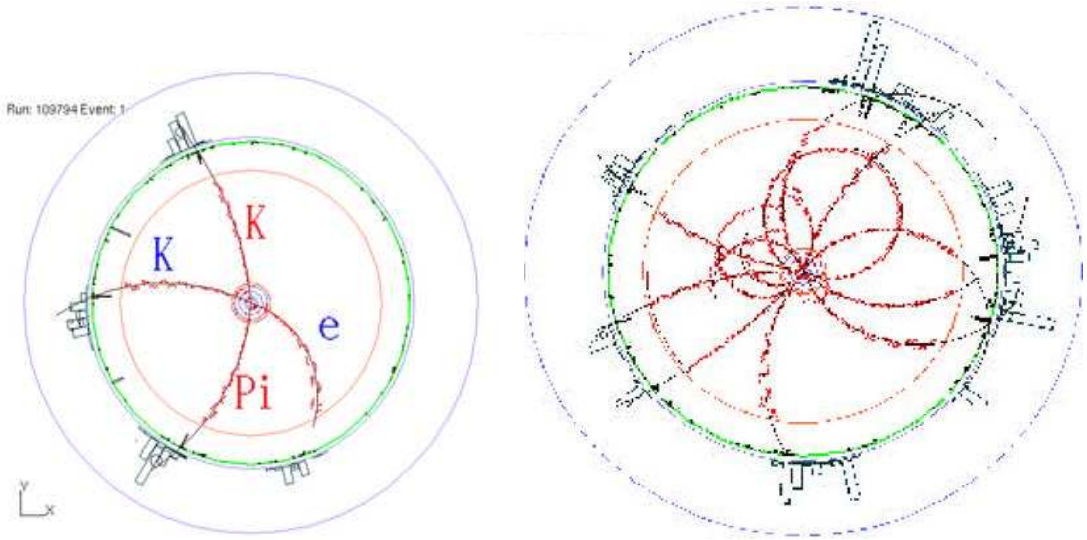
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cq}|^2 \, p_P^3 \left| f_+(q^2) \right|^2$$

  - V_{cs}, V_{cd} and form factors (test LQCD)

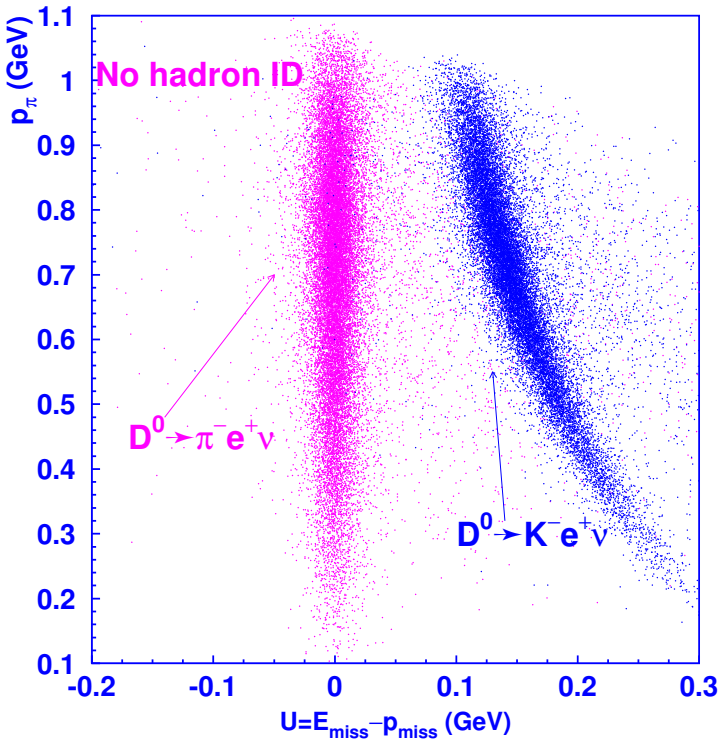
Advantages of $D\bar{D}$ production at the $\psi(3770)$

- large cross section ($\sigma_{D\bar{D}} \sim 6$ nb), low multiplicity ($\rightarrow$ clean events)

$\sqrt{s} = \psi(3770)$ $\quad$ $\sqrt{s} = \Upsilon(4S)$



- Unique kinematics: separate S/B



- many systematics cancel in $\mathcal{B}$ (Double tag)

Analysis Technique

- How to measure absolute $\mathcal{B}$?

1. D Tagging: one D hadronic decays to tag the $\bar{D}$ semileptonic decays

   ▷ D Tag: $N_{tag} = 2N_{D\bar{D}}\mathcal{B}_{tag}\epsilon_{tag}$ $\quad \begin{cases} M_{bc} = \sqrt{E^2_{beam} - p^2_D} \\ \Delta E = E_D - E_{beam} \end{cases}$

   ▷ D Semilep: $N_{sig} = 2N_{D\bar{D}}\mathcal{B}\mathcal{B}_{tag}\epsilon_{sig}$ $\quad U = E_{miss} - p_{miss}$ peaks @0.

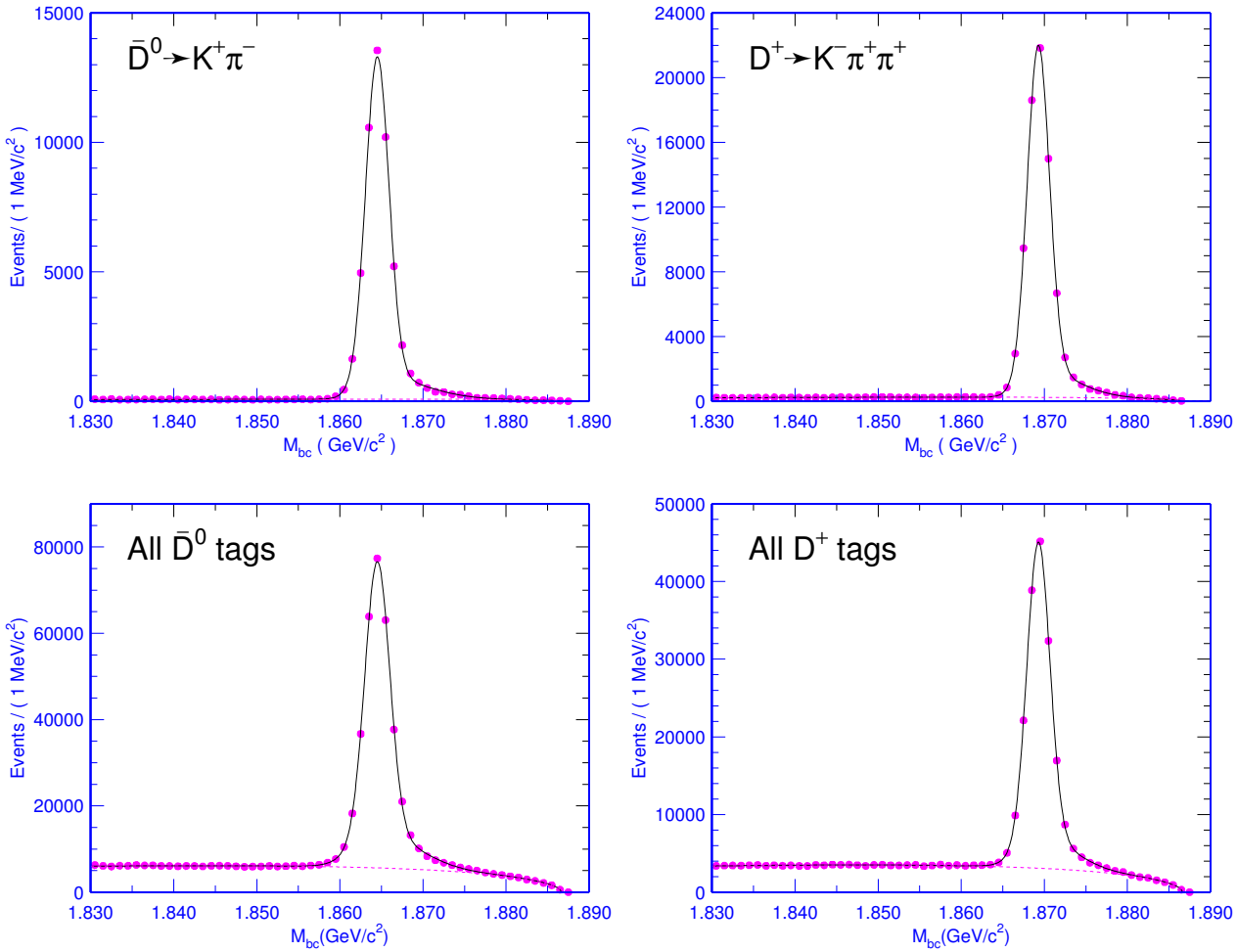
$$\Rightarrow \quad \mathcal{B} = \frac{N_{sig}/\epsilon_{sig}}{N_{tag}/\epsilon_{tag}} = \frac{N_{sig}}{N_{tag}\epsilon_{sig}/\epsilon_{tag}}$$

2. Without D Tagging: neutrino reconstruction $\vec{\mathbf{p}}_\nu = \vec{\mathbf{p}}_{\mathbf{evt}} - (\vec{\mathbf{p}}_{\mathbf{chrg}} + \vec{\mathbf{p}}_{\mathbf{neu}})$

   ▷ D reconstructed by $\begin{cases} \Delta E = E_{had} + E_e + |\vec{\mathbf{p}}_\nu| - E_{beam} \\ M_{bc} = \sqrt{E^2_{beam} - (\vec{\mathbf{p}}_{\mathbf{had}} + \vec{\mathbf{p}}_{\mathbf{e}} + \vec{\mathbf{p}}_\nu)^2} \end{cases}$

   ▷ $\mathcal{B} = \frac{N_D}{2N_{D\bar{D}}\epsilon}$

Single D Tagging



- $\sim$308K D^0 tag

$\sim$163K D^+ tag fully reconstructed

Inclusive D Semileptonic Decays

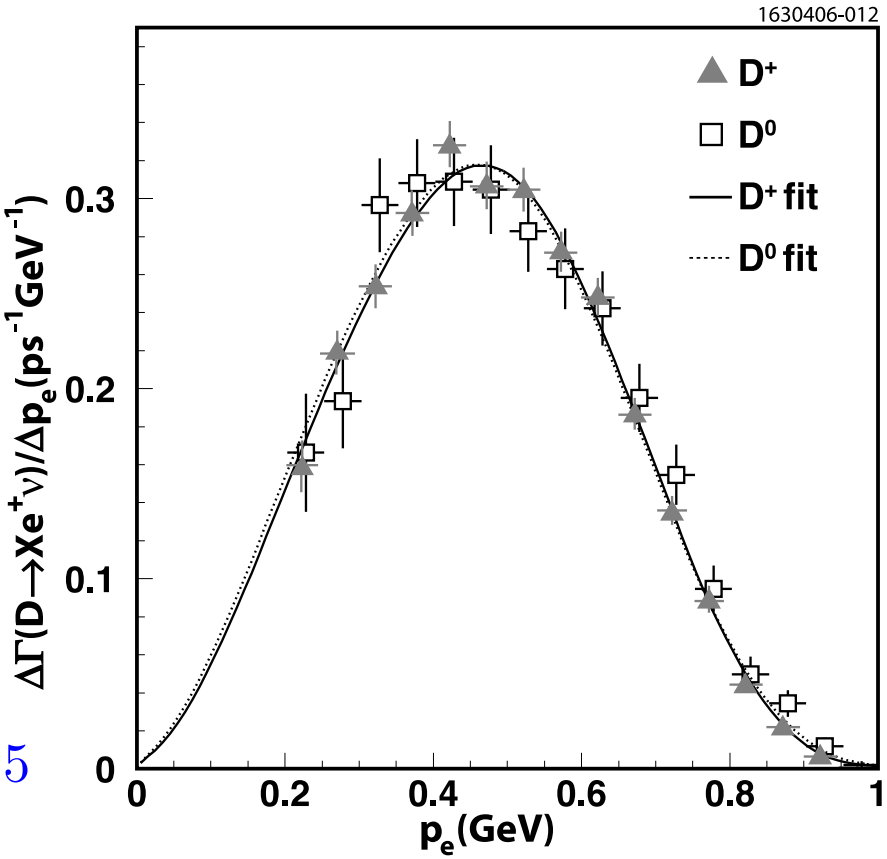
mode	branching fraction
$D^0 \to Xe^+\nu$	(6.46±0.17±0.13)%
$\sum_{excl.} \mathcal{B}(D^0 \to Xe^+\nu)$	(6.1±0.2±0.2)%
$D^+ \to Xe^+\nu$	(16.13±0.20±0.33)%
$\sum_{excl.} \mathcal{B}(D^+ \to Xe^+\nu)$	(15.1±0.5±0.5)%

- consistent with the known exclusive modes saturating the inclusive BR's

$$\frac{\Gamma^{SL}_{D^+}}{\Gamma^{SL}_{D^0}} = \frac{\mathcal{B}^{SL}_{D^+}}{\mathcal{B}^{SL}_{D^0}} \times \frac{\tau_{D^0}}{\tau_{D^+}} = 0.985 \pm 0.028 \pm 0.015$$

- consistent with isospin symmetry

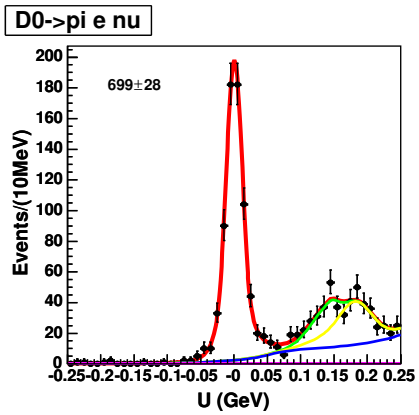
- hep-ex/0604044, submitted to PRL.

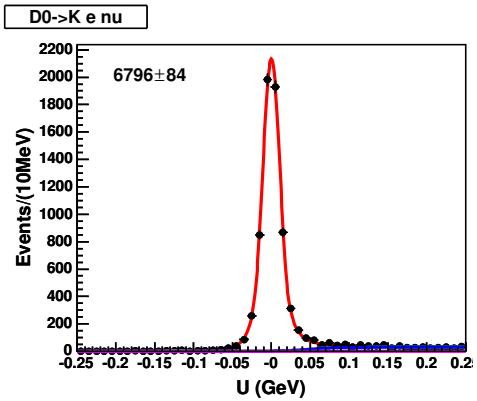


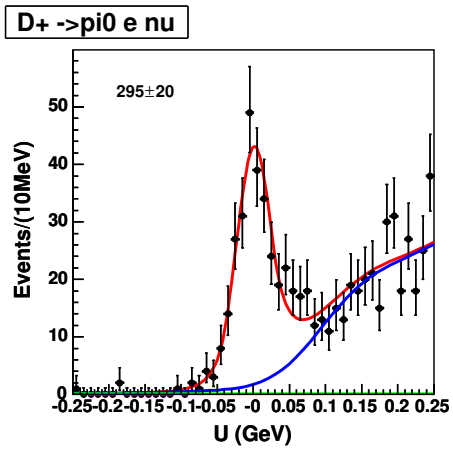
Extrapolated below $p_e < 0.2$ GeV/c.

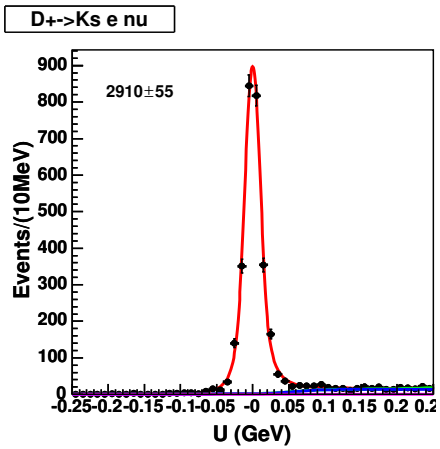
$D \to K/\pi e^+\nu$: Tagged and Untagged

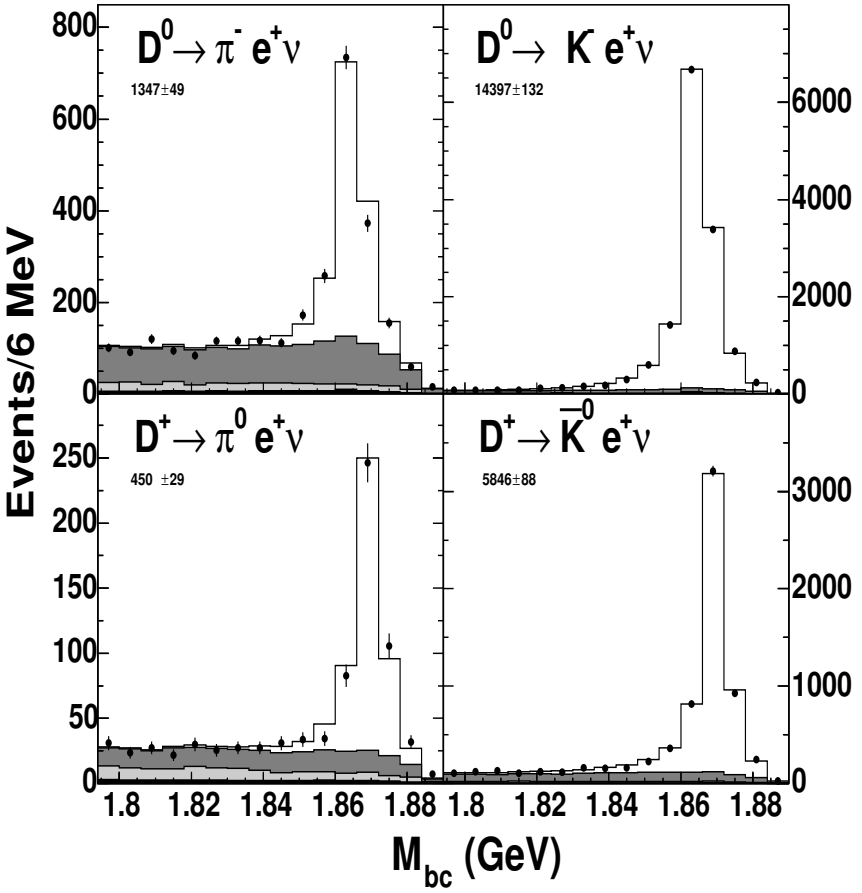
Tagged 40% common samples! Untagged











Results of D Semileptonic Decays

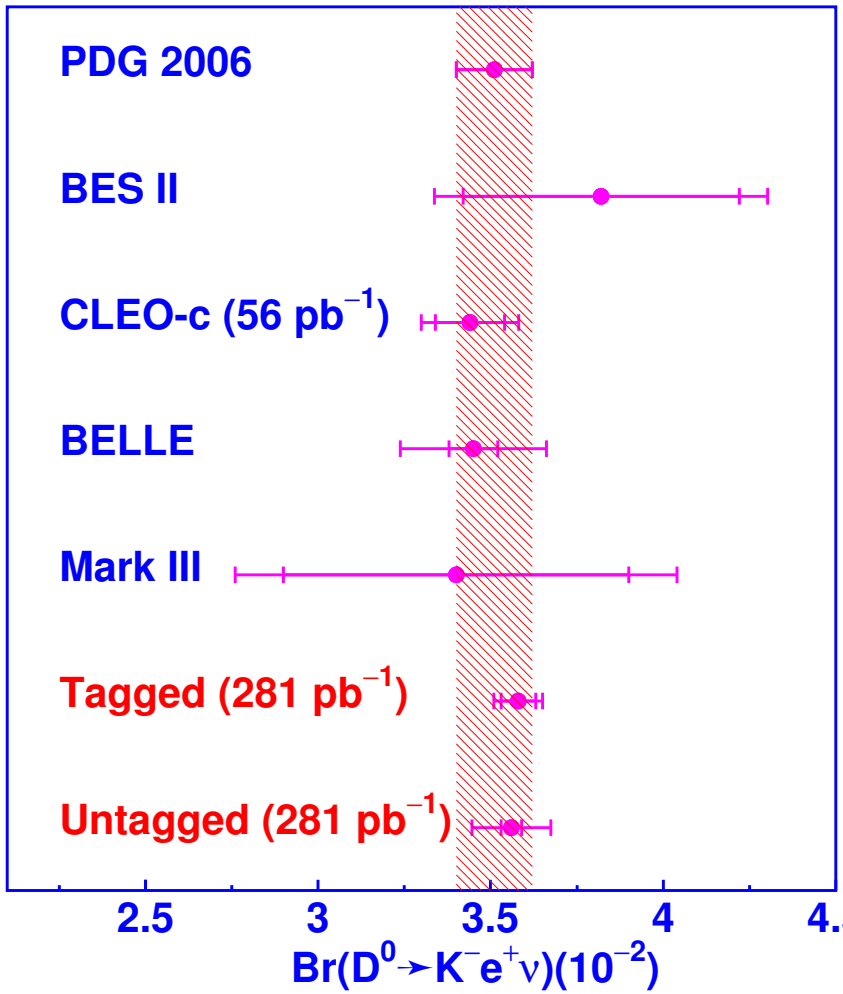
- D Semileptonic BR's

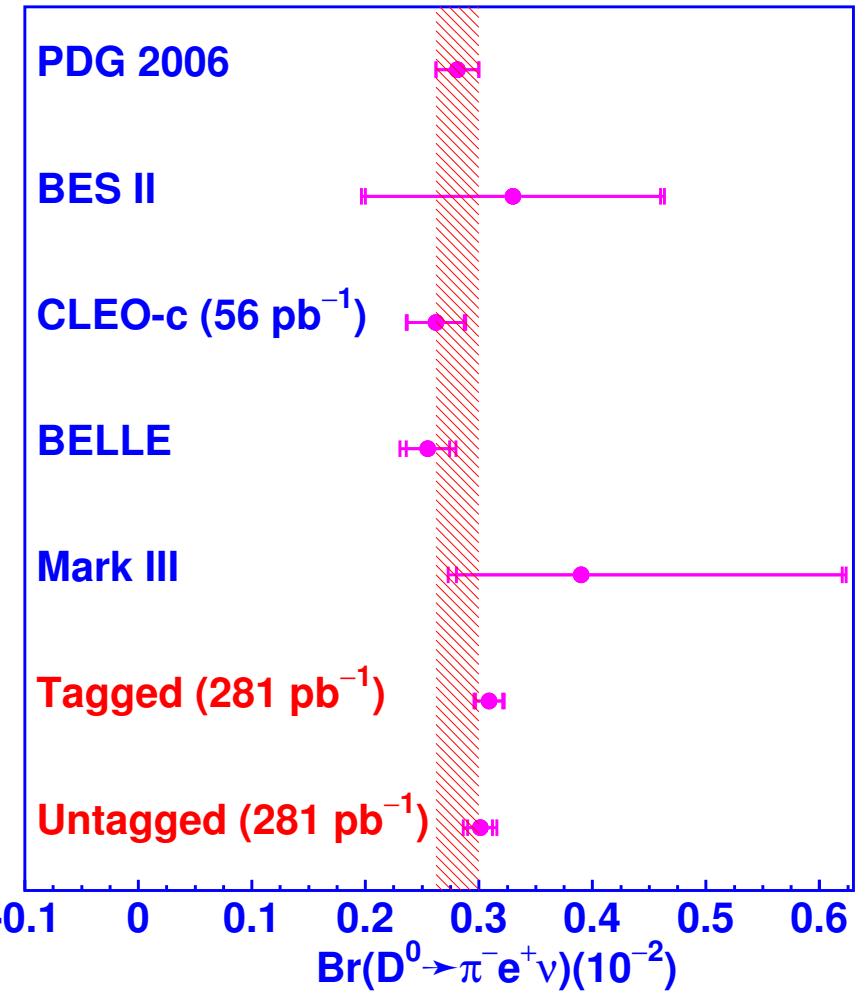
Mode	Tag (%)	Untag (%)	PDG'06 (%)
$D^0 \to K^- e^+ \nu$	3.58±0.05±0.05	3.56±0.03±0.11	3.51±0.11
$D^0 \to \pi^- e^+ \nu$	0.309±0.012±0.006	0.301±0.011±0.010	0.281±0.019
$D^+ \to \bar{K}^0 e^+ \nu$	8.86±0.17±0.20	8.75±0.13±0.30	8.6±0.5
$D^+ \to \pi^0 e^+ \nu$	0.397±0.027±0.028	0.383±0.025±0.016	0.44±0.07

Ratio	$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D^0 \to K^- e^+ \nu)}$	$\frac{\Gamma(D^0 \to \pi^- e^+ \nu)}{\Gamma(D^+ \to \pi^0 e^+ \nu)}$	$\frac{\Gamma(D^0 \to K^- e^+ \nu)}{\Gamma(D^+ \to K^0 e^+ \nu)}$
CLEO-c	(8.5±0.3±0.1)%	1.95±0.15±0.14	1.02±0.02±0.02
		1.99±0.15±0.10	1.03±0.02±0.04
PDG'06	8.0±0.6		

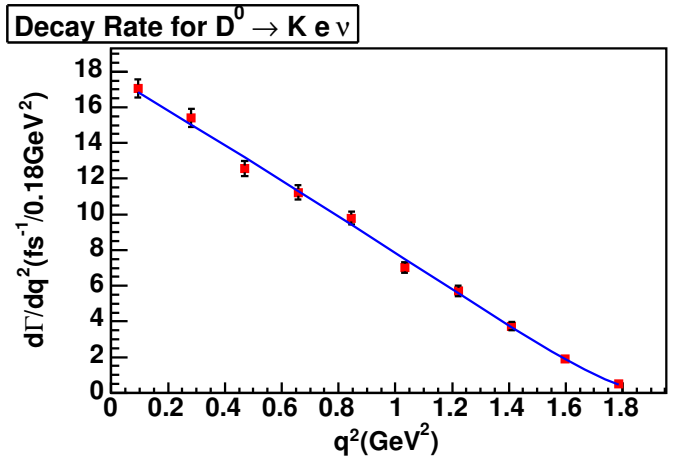
- More precise results
- Ratios of $\frac{\Gamma_{D^0}}{\Gamma_{D^+}}$ consistent with isospin symmetry
- PDG'06 dominated by CLEO-c results from 56 pb^{-1}

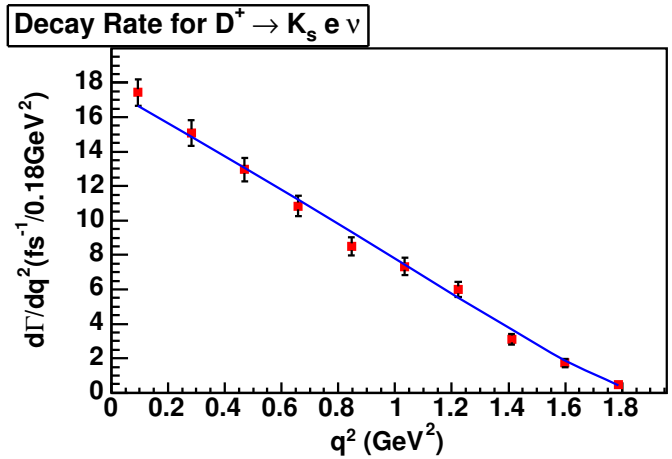
Comparison with Other Results

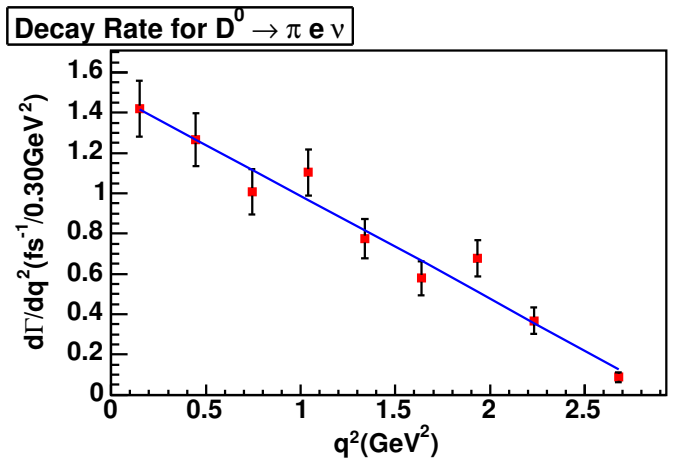


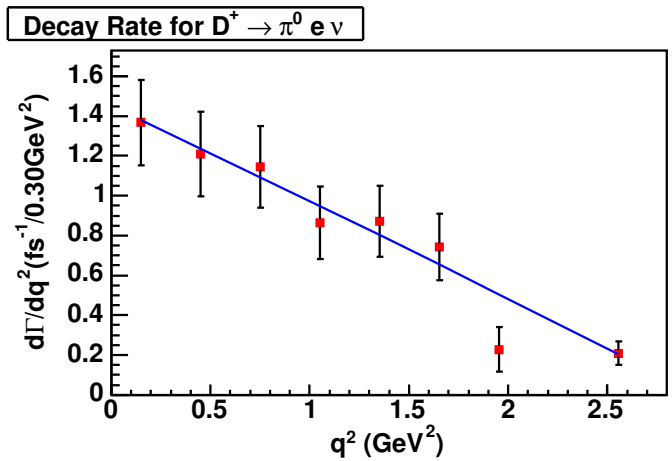


Form Factor Fits (Tagged)



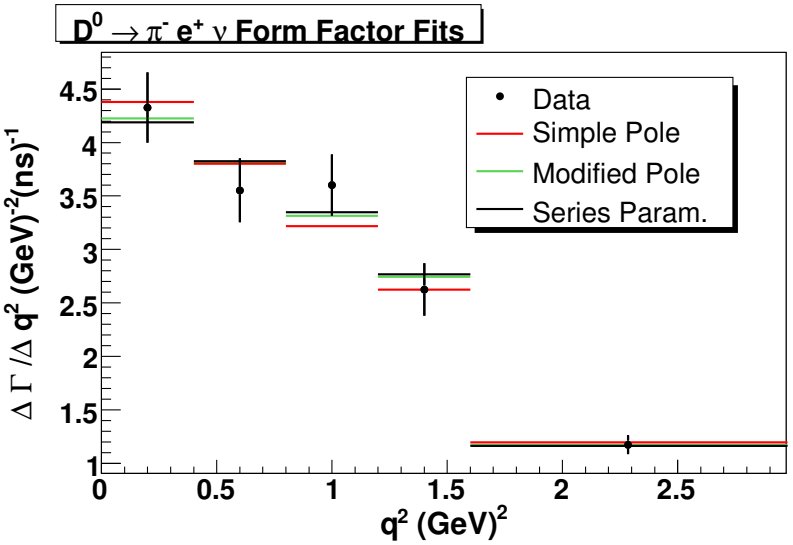


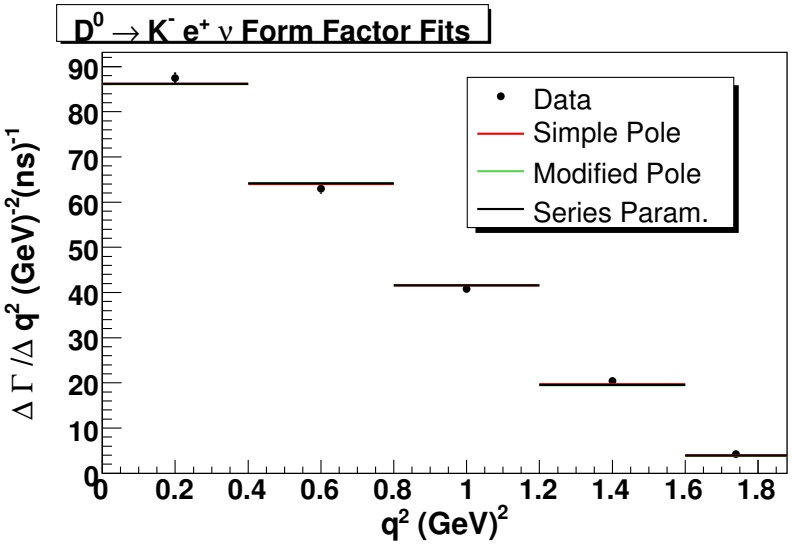


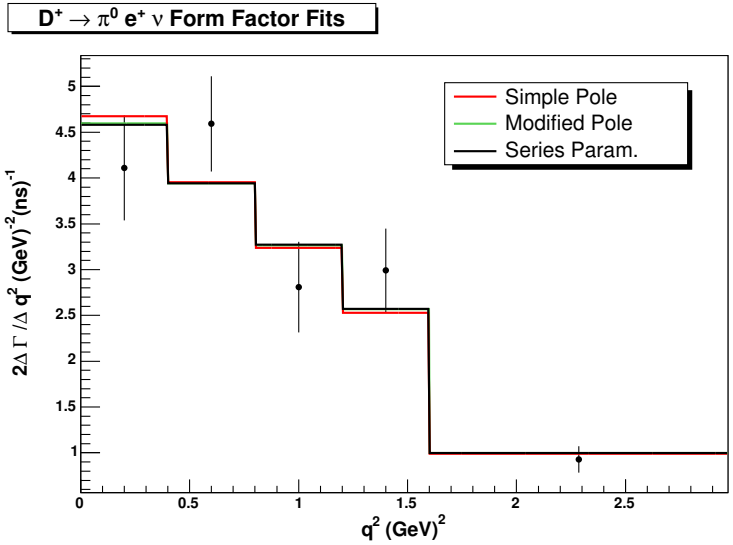


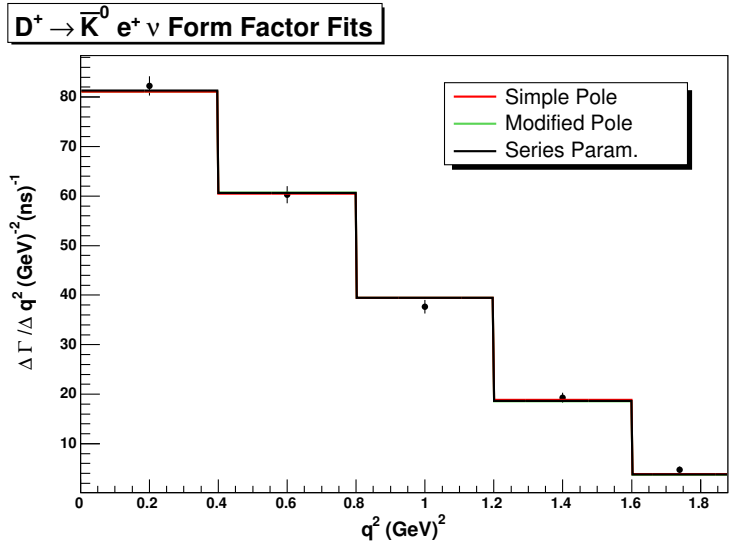
- Modified pole $f_+(q^2) = \frac{f_+(0)}{(1-q^2/M^2_{pole})(1-\alpha q^2/M_{pole})} \Rightarrow$ simple pole ($\alpha = 0$).
- Hill series expansion (Phys. Lett. **B633**, 61 (2006).

Form Factor Fits (Untagged)

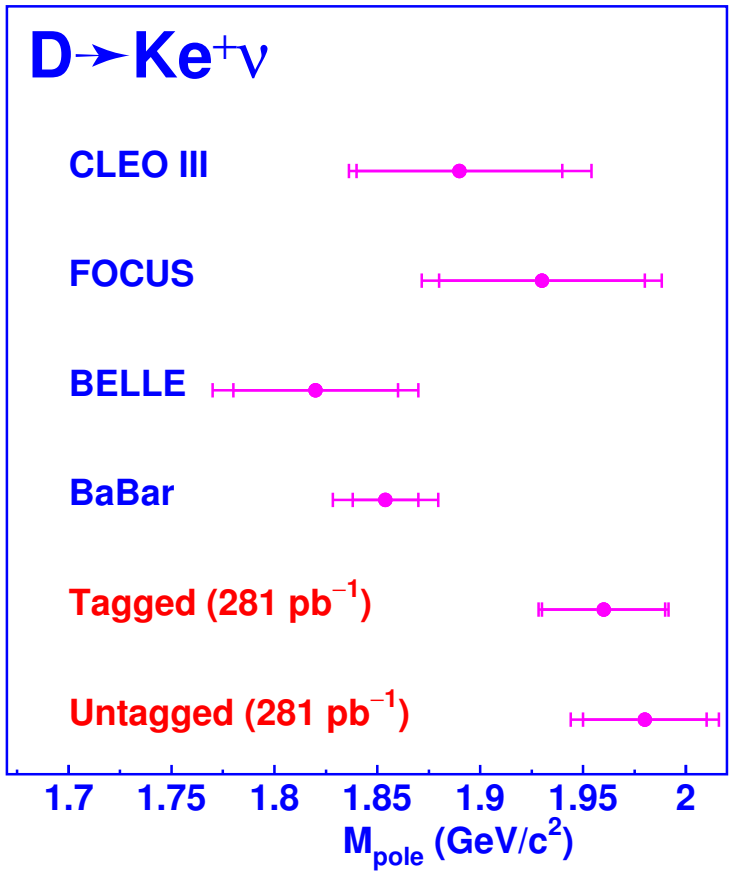


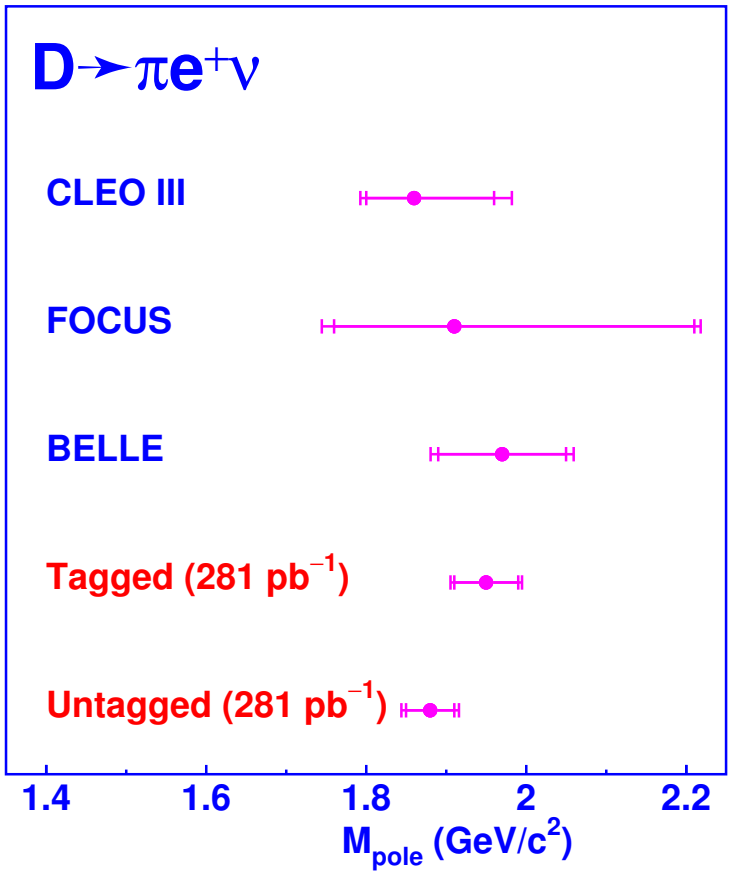






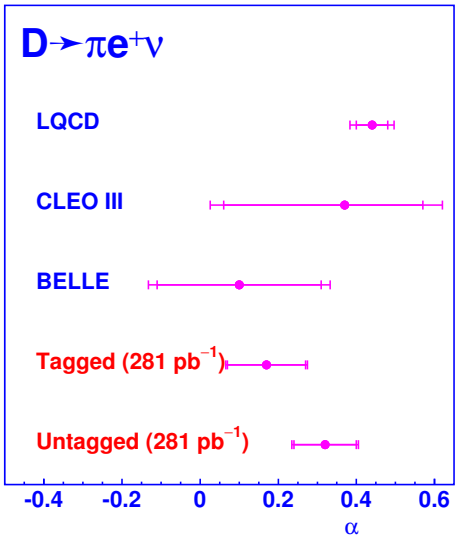
Form Factor Fits (Tagged/Untagged)

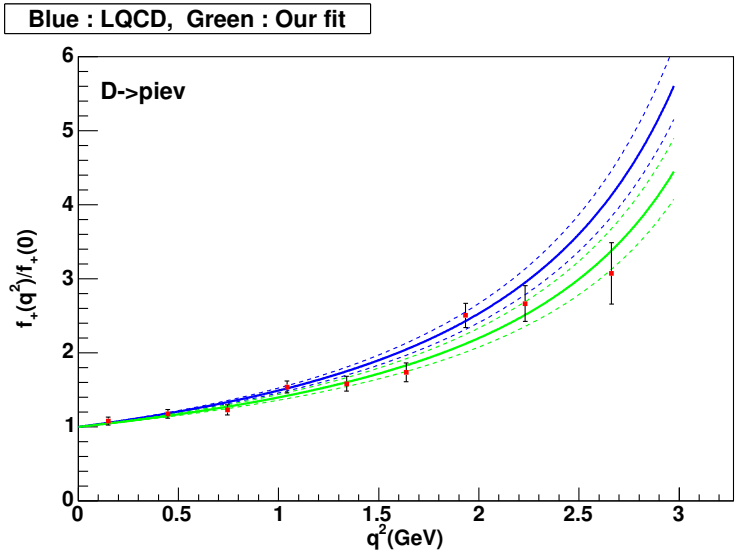


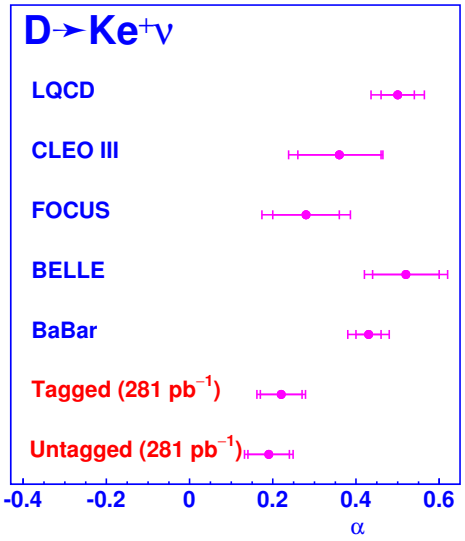


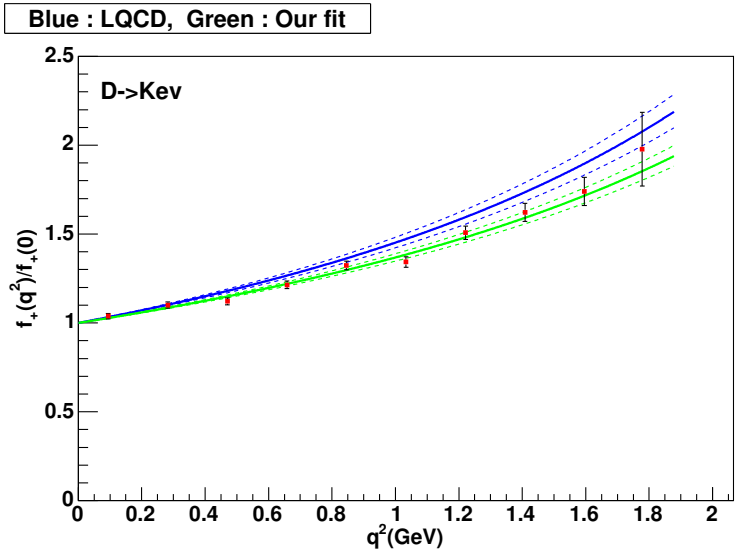
Mode	M_{pole} (Tagged)	M_{pole} (Untagged)
$D \to Ke\nu$	1.96±0.03±0.01	1.98±0.03±0.02
$D \to \pi e\nu$	1.95±0.04±0.02	1.88±0.03±0.02

Form Factors and Tests of LQCD







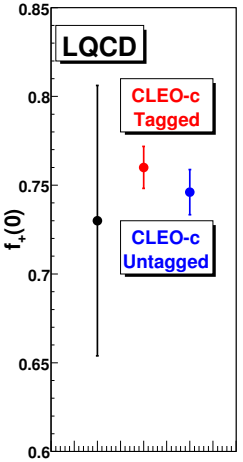


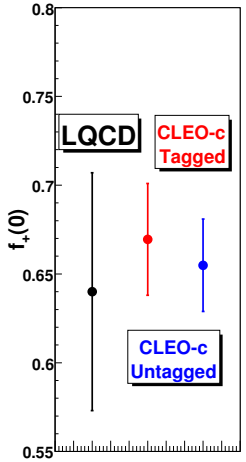
V_{cs} and V_{cd} Results

With $f_+(0)$ from unquenched LQCD (PRL 94, 011601 (2005)) and $V_{cx}f_+(0)$ values from fits $\rightarrow$ V_{cs} and V_{cd}

Mode	$V_{cx} \pm (stat.) \pm (sys.) \pm (theory)$	PDG'06
$D \rightarrow \pi e\nu$ (tagged)	0.234±0.010±0.004±0.024	0.230±0.011
$D \rightarrow \pi e\nu$ (untagged)	0.229±0.007±0.005±0.024	0.230±0.011
$D \rightarrow Ke\nu$ (tagged)	0.996±0.008±0.015±0.104	0.957±0.095
$D \rightarrow Ke\nu$ (untagged)	1.014±0.013±0.009±0.106	0.957±0.095

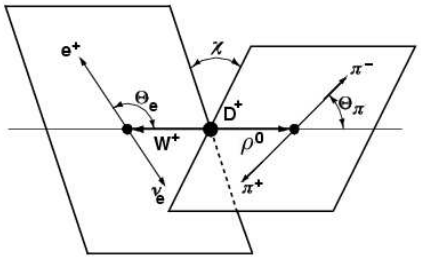
- Expt.uncertainty $V_{cs} < 2\%$,$V_{cd} < 4\%$, LQCD$\sim$ 10%.
- Alternatively, V_{cs} $(W \rightarrow cs)$ and $V_{cd} = -V_{us}$ from other experiments, we determine $f_+(0)$ (<2% for $f_+(0)^K$, $< 4\%$ for $f_+(0)^\pi$) to test LQCD ($\sim$10%).
- Tagged/Untagged: 40% overlap, DO NOT AVERAGE
- Results from untagged method are about to be submitted to PRL and PRD





$D \to \rho e^+ \nu$

- Five variables: q^2, $\cos\theta_\ell$, $\cos_V$, χ and M_V
  $d\Omega \equiv dq^2 d\cos\theta_\pi d\cos\theta_e d\chi dm(\pi\pi)$
  4-D (q^2, $\cos\theta_\ell$, $\cos_V$, χ) fit to data



$$\frac{d\Gamma}{d\Omega} = \mathcal{B}(\rho\to\pi\pi)\frac{3G_F^2|V_{cd}|^2}{8(4\pi)^4}p_{\rho 0}\,q^2\,BW(m(\pi\pi))\times\Big\{(1+\cos\theta_e)^2\sin^2\theta_\pi|H_+(q^2,m(\pi\pi))|^2$$
$$+(1-\cos\theta_e)^2\sin^2\theta_\pi|H_-(q^2,m(\pi\pi))|^2+4\sin^2\theta_e\cos^2\theta_\pi|H_0(q^2,m(\pi\pi))|^2$$
$$+4\sin\theta_e(1+\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_+(q^2,m(\pi\pi))H_0(q^2,m(\pi\pi))$$
$$-4\sin\theta_e(1-\cos\theta_e)\sin\theta_\pi\cos\theta_\pi\cos\chi H_-(q^2,m(\pi\pi))H_0(q^2,m(\pi\pi))$$
$$-2\sin^2\theta_e\sin^2\theta_\pi\cos 2\chi H_+(q^2,m(\pi\pi))H_-(q^2,m(\pi\pi))\Big\}$$

$$H_\pm(q^2) = (M_D+M_V)A_1(q^2)\mp 2\frac{M_D p_V}{M_D+M_V}V(q^2),$$

$$H_0(q^2) = \frac{1}{2M_V\sqrt{q^2}}\left[\left(M_D^2-M_V^2-q^2\right)(M_D+M_V)\,A_1(q^2)-4\frac{M_D^2p_V^2}{M_D+M_V}A_2(q^2)\right]$$

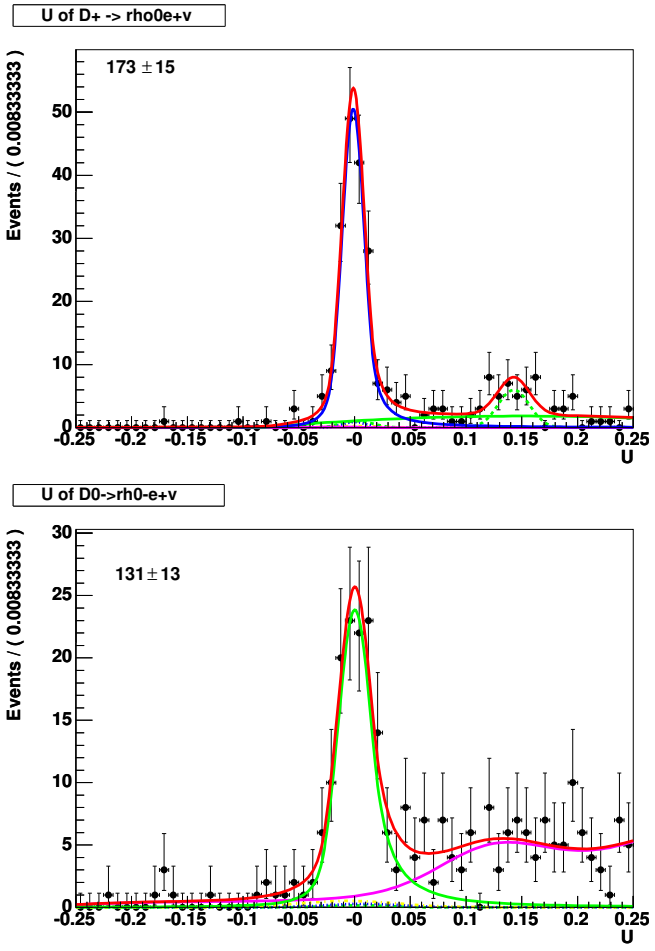
$$A_{1(2)}(q^2)=\frac{A_{1(2)}(0)}{1-q^2/M_A^2}\qquad V(q^2)=\frac{V(0)}{1-q^2/M_V}\qquad R_V\equiv\frac{V(0)}{A_1(0)}\qquad R_2\equiv\frac{A_2(0)}{A_1(0)}$$

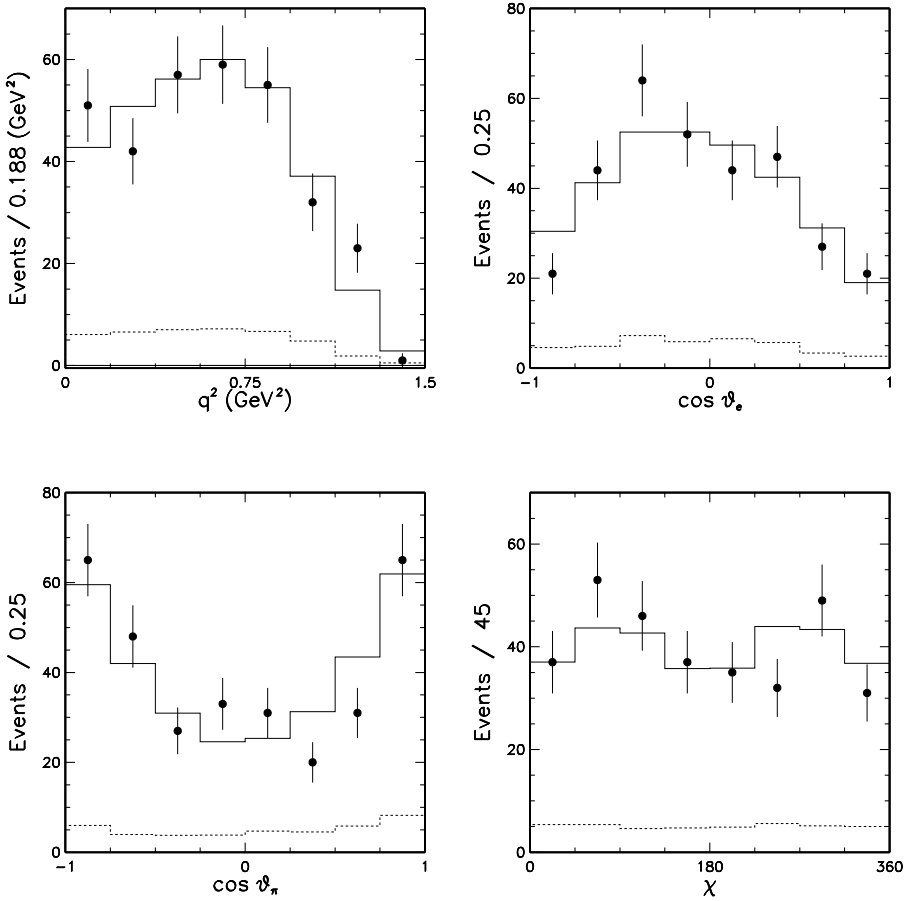
Form Factors in $D \to \rho e^+ \nu$

- Improved BR's

  $\mathcal{B}(D^0) = (1.56 \pm 0.16 \pm 0.09) \times 10^{-3}$

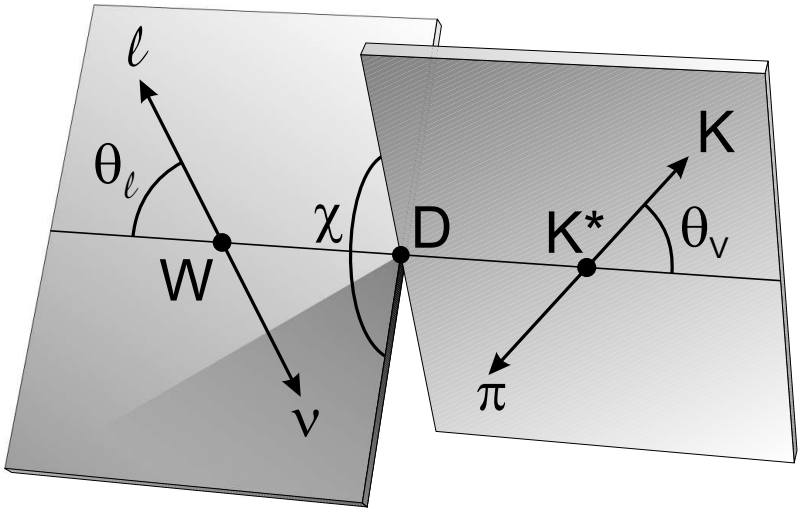
  $\mathcal{B}(D^+) = (2.32 \pm 0.20 \pm 0.12) \times 10^{-3}$





- $R_V = 1.40 \pm 0.25 \pm 0.03$,
  $R_2 = 0.57 \pm 0.18 \pm 0.06$
- First measurement of FF

$D^+ \to K^-\pi^+e^+\nu$



- $\frac{d\Gamma}{d\cos\theta_\ell d\cos\theta_V d\chi dq^2 dm_V}$
- $A_{1(2)}(q^2) = \frac{A_{1(2)}(0)}{1-q^2/M_A^2}$,
  $V(q^2) = \frac{V(0)}{1-q^2/M_V^2}$
  $R_V \equiv \frac{V(0)}{A_1(0)}$, $R_2 \equiv \frac{A_2(0)}{A_1(0)}$

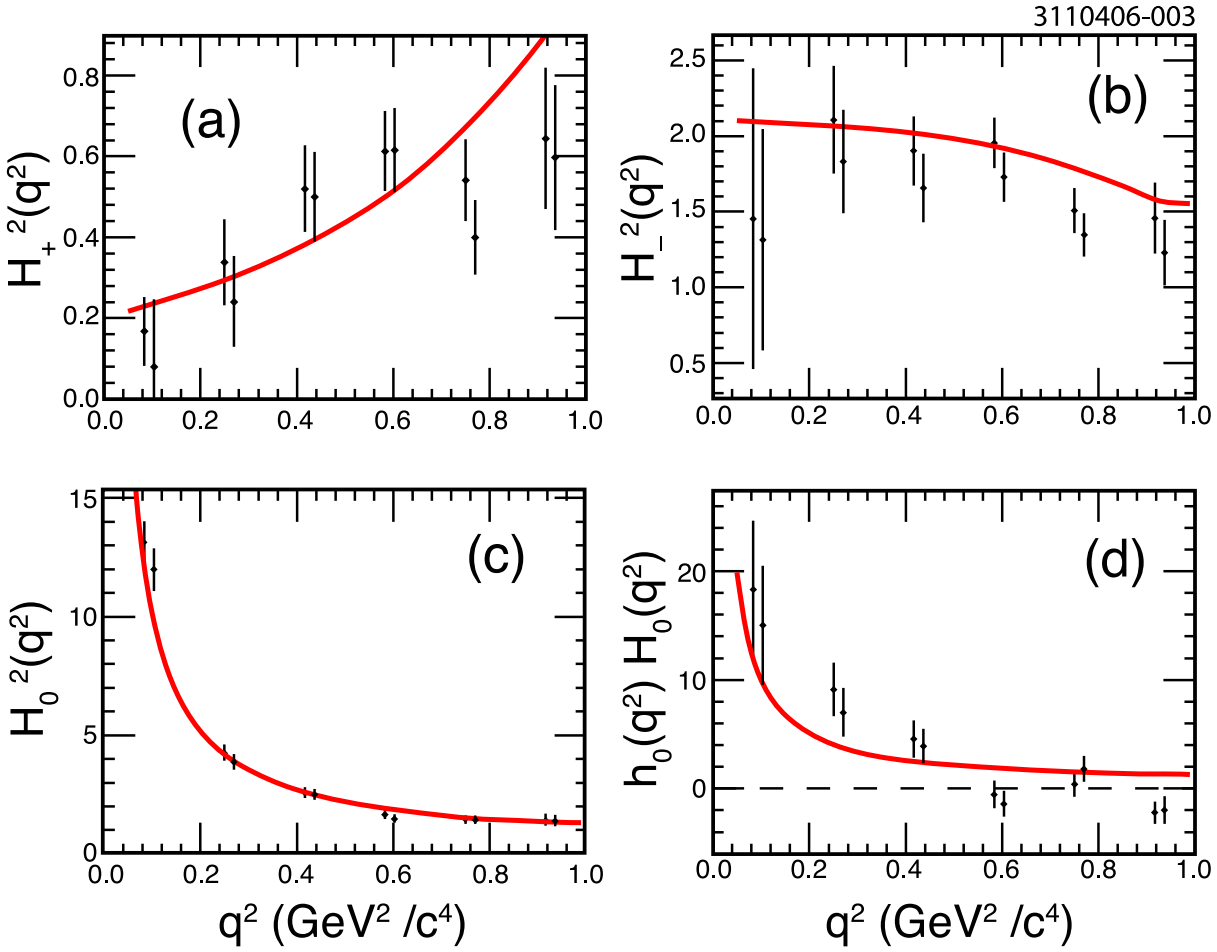
$$\int |A|^2 d\chi \propto \left\{ \begin{array}{l} ((1+\cos\theta_\ell)\sin\theta_V)^2 |H_+(q^2)|^2 |\mathrm{BW}|^2 \\ +((1-\cos\theta_\ell)\sin\theta_V)^2 |H_-(q^2)|^2 |\mathrm{BW}|^2 \\ +(2\sin\theta_\ell\cos\theta_V)^2 |H_0(q^2)|^2 |\mathrm{BW}|^2 \\ +8\sin^2\theta_\ell\cos\theta_V H_0(q^2) h_0(q^2) \mathrm{Re}\{A e^{-i\delta}\mathrm{BW}\} \\ \mathcal{O}(A^2) \end{array} \right\}$$

$$H_\pm(q^2) = (M_D + M_V)A_1(q^2) \mp 2\frac{M_D p_V}{M_D + M_V} V(q^2),$$

$$H_0(q^2) = \frac{1}{2M_V\sqrt{q^2}} \left[\left(M_D^2 - M_V^2 - q^2\right)(M_D + M_V) A_1(q^2) - 4\frac{M_D^2 p_V^2}{M_D + M_V} A_2(q^2) \right],$$

(S-wave $h_0 = H_0$ assumed when present in K^*)

Form Factors in $D^+ \to K^-\pi^+e^+\nu$

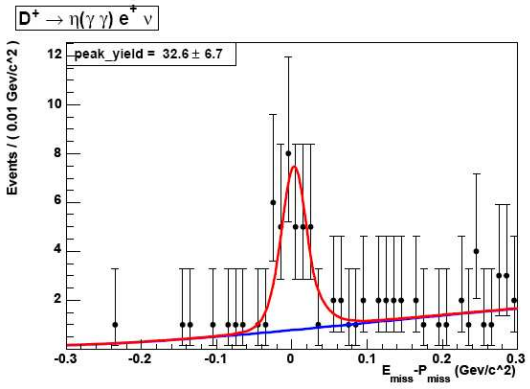


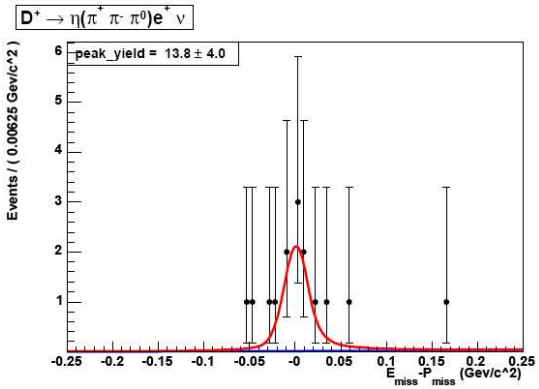
- significant S-wave amp. confirmed ($h_0 \neq 0$), no evidence for d- or f-wave (PRD **74** 052001 (2006), two sets of event selection)

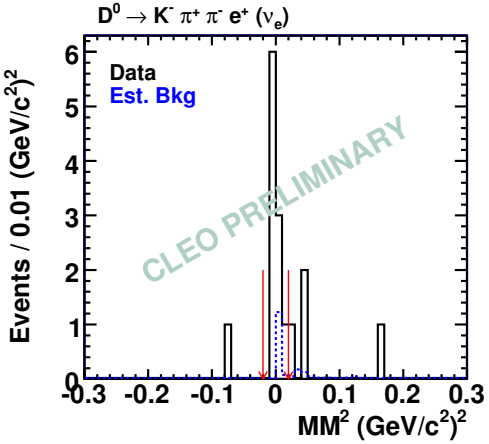
Rare D Semileptonic Decays

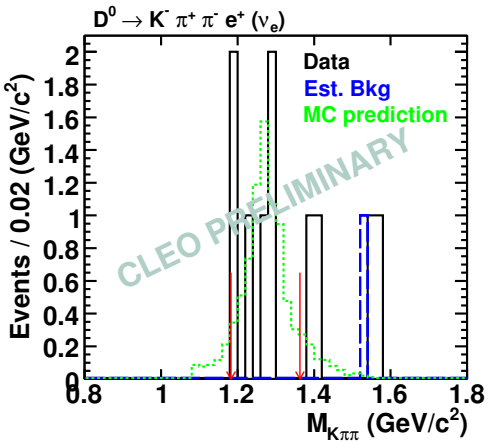
- L=281 pb^{-1}, all results are preliminary

Mode	$\mathcal{B}(\times 10^{-4})$
$\eta e^+\nu$	12.9±1.9±0.7
$K^-\pi^+\pi^-e^+\nu$	$2.9^{+1.5}_{-1.1}$±0.5
$K_1(1270)e^+\nu$	$2.2^{+1.4}_{-1.1}$±0.2
$\omega e^+\nu$	14.9±2.7±0.5
$\eta' e^+\nu$	<3 (@ CL=90%)
$\phi e^+\nu$	<2 (@ CL=90%)







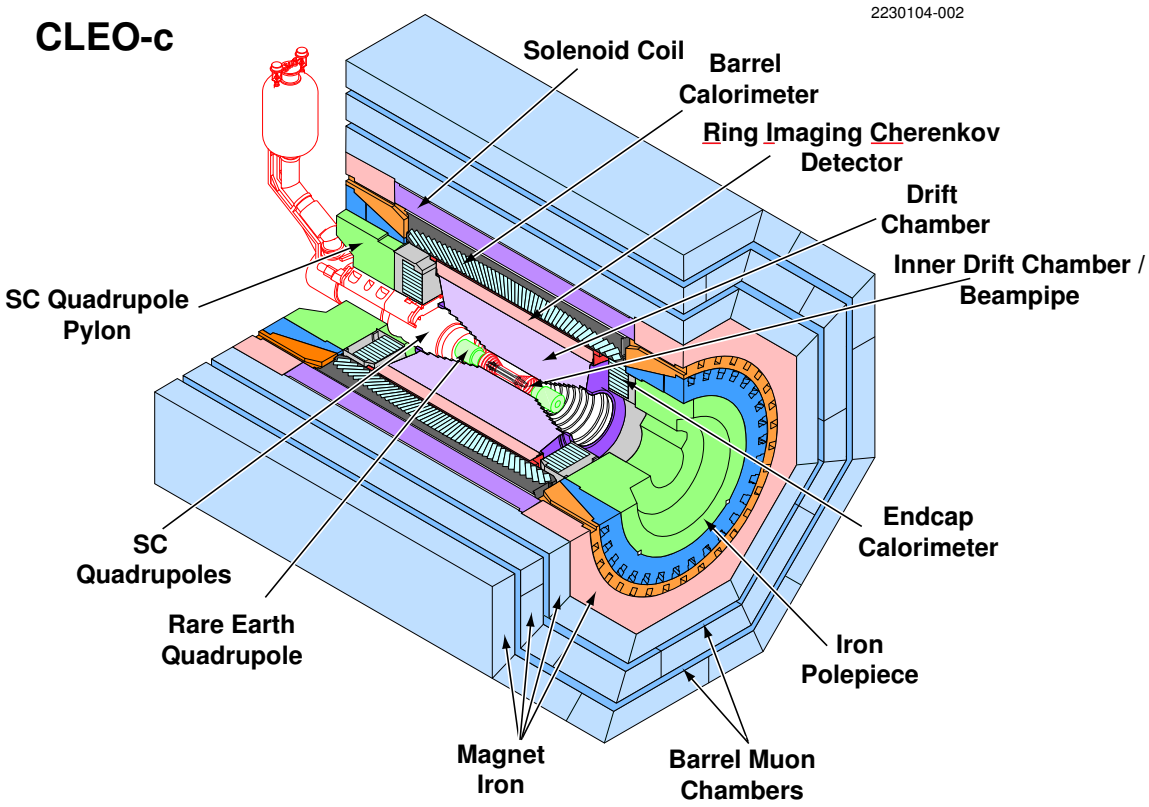


- first observation of $\eta e^+\nu$ and $K^-\pi^+\pi^-(K_1)e^+\nu$
- improved $\mathcal{B}(\omega e^+\nu)$ and ULs for $\eta' e^+\nu$ and $\phi e^+\nu$.

Summary

- Precise inclusive lepton spectra
- Precise D semileptonic BR's $\rightarrow V_{cs}$ and V_{cd}
- Precise results on $D \rightarrow Pe^+\nu$ form factors to test LQCD
- First study of FF in $D \rightarrow \rho e^+\nu$ and confirmed significant S-wave amplitude in $D^+ \rightarrow K^{*0}e^+\nu$.
- Seach for new mode, first observation of $\eta e^+\nu$ and $K^-\pi^+\pi^-e^+\nu$
- We expect further improvement with more data (750 pb^{-1} planned).

CLEO-c Detector



- CLEO-c:
  - ◇ B=1 T;
  - ◇ tracking (93% of 4π)
    - ▷ 16 axial, 31 stereo lay.
    - ▷ $\sigma_p/p \sim 0.6\%$
  - ◇ CsI (95% of 4π)
    - ▷ σ_E/E ~5% @ 0.1 GeV
      ~2.2% @ 1 GeV
  - ◇ Hadron ID
    - ▷ RICH (80% of 4π)+dE/dx
    - ▷ ϵ_K>90% w/ few% fakes
  - ◇ Electron ID
    - ▷ RICH+dE/dx + CsI